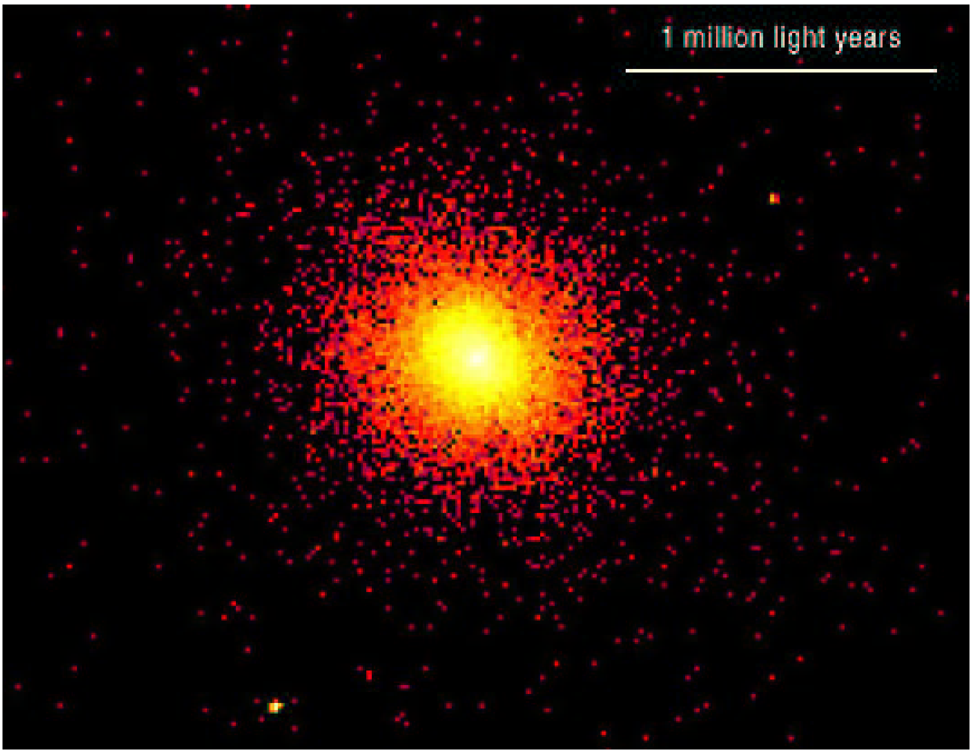
Cosmological constraints from Chandra observations of galaxy clusters



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PROJECT OUTLINE:

Last four years, we have carried out a programme to study most X-ray luminous, dynamically relaxed galaxy clusters identified from ROSAT All-Sky Survey.

Aims: measure mass distributions using Chandra X-ray data and independent gravitational lensing studies → improved constraints on cosmological parameters ($\Omega_{\rm m}, \Omega_\Lambda, \sigma_8$, w ...)

THIS TALK (cosmological constraints):

Constraints on $\Omega_{\rm m}$, Ω_Λ from the X-ray gas mass fraction, $f_{\rm gas}$, in dynamically relaxed clusters and its apparent redshift dependence.

— precise constraint on $\Omega_{\rm m}$.
— confirmation of SNIa results on dark energy.

Constraints on σ_8, $\Omega_{\rm m}$ from local X-ray luminosity function (XLF).

Results from combination of Cosmic Microwave Background (WMAPext) and Chandra $f_{\rm gas}(z)$ data.

— combination of data sets breaks degeneracies in each
→ tight constraints on key cosmo. params. (H_0, $\Omega_{\rm q}$, w).

— (with XLF data) → preference for a non-zero neutrino mass.

X-RAY MASS MEASUREMENTS:

Divide clusters into circular annuli (2D) or spherical shells (3D).

$\longrightarrow$ 1) observed X-ray surface brightness profile
2) deprojected (spectrally-determined) kT profile

+ assump. hydrostatic equilibrium (spherical symmetry) $\rightarrow$ M(r).

In practise, studies of distant clusters require modified approach: Take simple parameterized mass model (NFW: $r_{\rm s}, c$) + SB(r) $\rightarrow$ run Monte-Carlo simulations predict kT(r) $\rightarrow$ compare with obs.

Examine grid 100×100 parameter values for each mass model. Evaluate χ^2 for each grid point $\rightarrow$ best-fit model + uncertainties.

LENSING STUDIES:

Weak lensing: ($r \gtrsim 200h_{50}^{-1}$ kpc)

Results from literature + own programmes underway.

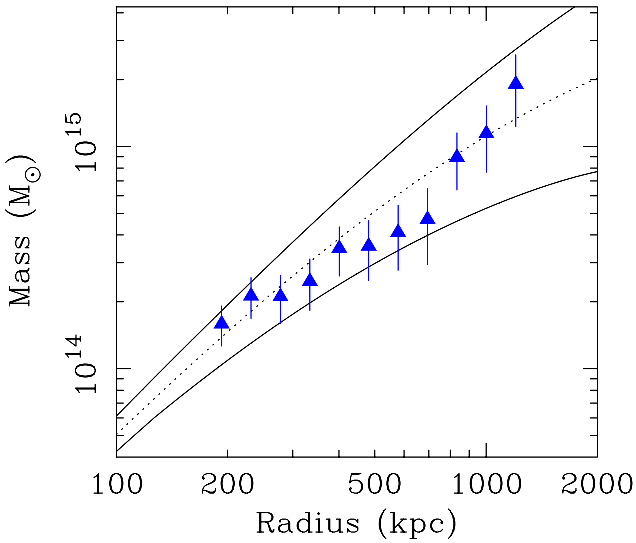
Strong lensing: ($r \lesssim 200h_{50}^{-1}$ kpc)

Ground based programme complete. HST (WFPC2/ACS) programme underway.

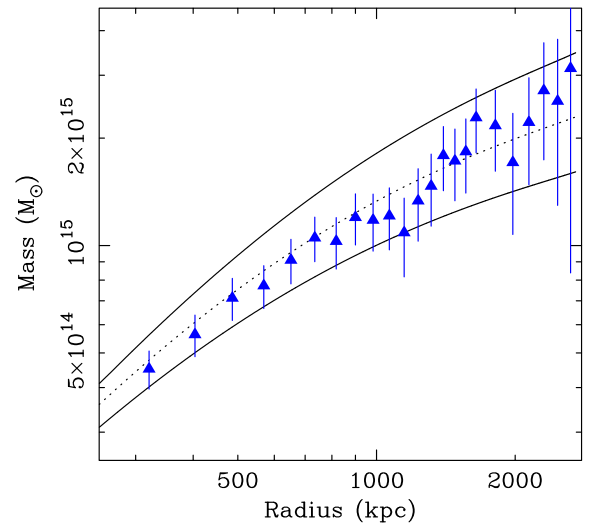
KEY: Combination of independent X-ray plus lensing methods $\rightarrow$ robust results!

X-RAY + WEAK LENSING:

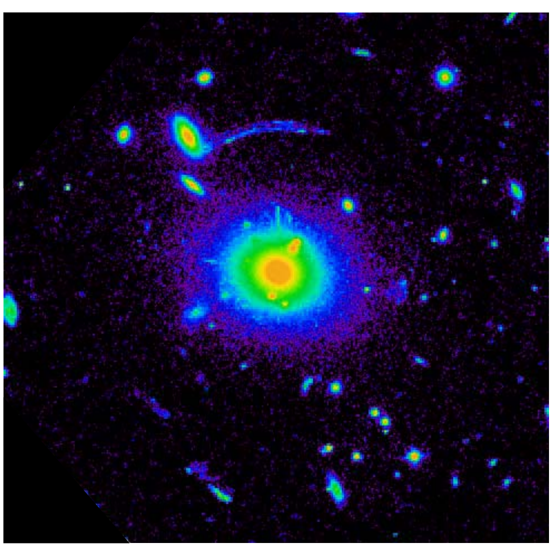
Abell 2390

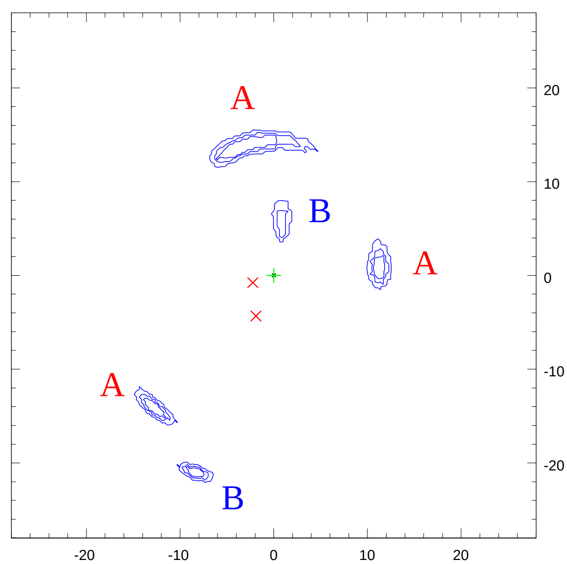


RXJ1347.5-1145



STRONG LENSING IN MS2137.3-2353:





Excellent agreement between observed and predicted arc configurations, only free parameters background source positions.

Cosmological constraints from the X-ray gas mass fraction in the most luminous, relaxed galaxy clusters

References: White & Frenk (1991). Fabian (1991), White *et al.* (1993), David *et al.* (1995), White & Fabian (1995), Evrard (1997), Ettori & Fabian (1999), Allen *et al.* (2002, 2003), Ettori *et al.* (2003), Arnaud *et al.* (2003).

BASIC IDEA: Galaxy clusters are so large that their matter content should provide a fair sample of matter content of Universe.

Chandra + lensing data → robust total mass measurements
Chandra data → (very) precise X-ray gas mass measurements

X-ray gas dominates baryonic mass content of clusters (6-7 times more mass than all stars in galaxies *e.g.* Fukugita *et al.* 1998).

If we define:

$$f_{\rm gas} = \frac{\text{Xray gas mass}}{\text{total mass in cluster}} \qquad\qquad f_{\rm gal} = 0.19h^{0.5} f_{\rm gas}$$

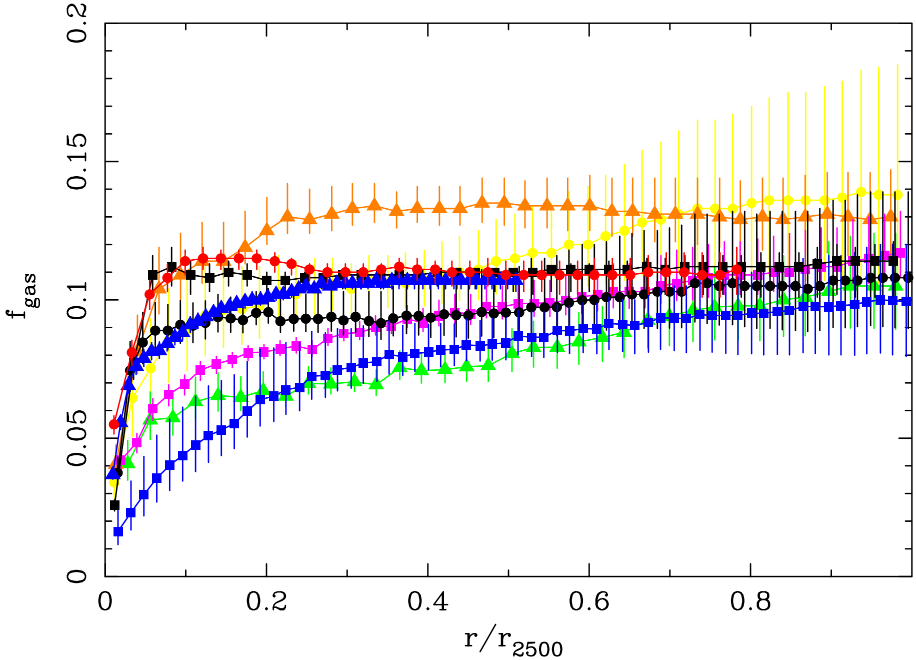
Then $$f_{\rm baryon} = f_{\rm gal} + f_{\rm gas} = f_{\rm gas}(1 + 0.19\,\mathrm{h}^{0.5}).$$

Since clusters provide fair sample of Universe, $f_{\rm baryon} = \Omega_{\rm b}/\Omega_{\rm m}$.

$$\Omega_{\rm m} = \frac{\Omega_{\rm b}}{f_{\rm baryon}} = \frac{\Omega_{\rm b}}{f_{\rm gas}(1 + 0.19\,\mathrm{h}^{0.5})}$$

So given $f_{\rm gas}$, $\Omega_{\rm b}$ (cosmic nucleosynthesis, CMB) $\longrightarrow \Omega_{\rm m}$.

CHANDRA RESULTS on $f_{\rm gas}(r)$ (ΛCDM)



(fig from Allen *et al.* 2003. Data analysed here has 10 clusters.)

$f_{\rm gas}(r) \rightarrow$ approximately universal value at $r \sim r_{2500}$

$$\rightarrow \text{weighted mean } \bar{f}_{\rm gas}(r_{2500}) = (0.110 \pm 0.003) h_{70}^{-1.5} = (0.065 \pm 0.002) h^{-1.5}$$

Given $\Omega_{\rm b}\,{\rm h}^2 = 0.0214 \pm 0.0020$ (Kirkman *et al.* 2003)

$h = H_0/100 = 0.72 \pm 0.08$ (Freedman *et al.* 2001)

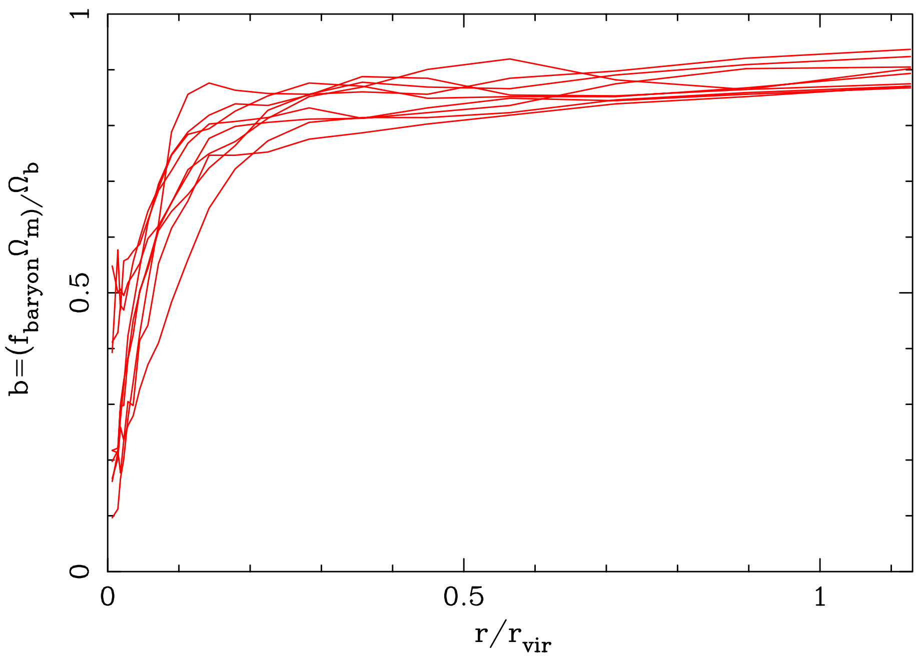
$$\Longrightarrow \quad \Omega_{\rm m} = \frac{(0.0214 \pm 0.0020) h^{-0.5}}{(0.065 \pm 0.002)(1 + 0.19\,{\rm h}^{0.5})}$$

$$= \quad 0.323 \pm 0.031$$

Indication from simulations that baryonic mass fraction in clusters is slightly lower than mean value for universe as a whole.

$$f_{\mathrm{baryon}} = b\,\frac{\Omega_{\mathrm{b}}}{\Omega_{\mathrm{m}}}$$

e.g. Eke, Navarro & Frenk (1998)



For $r = 0.25\,r_{\mathrm{vir}}$ (Chandra obs.) $\quad b = 0.83 \pm 0.04$

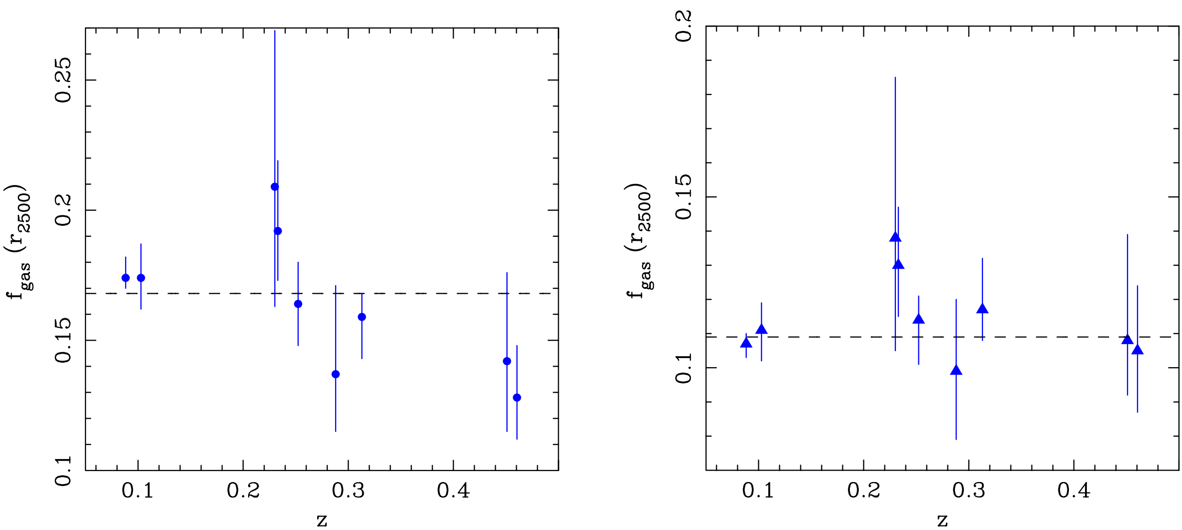
$$\longrightarrow \Omega_{\mathrm{m}} = 0.27 \pm 0.03$$

Apparent variation of $f_{\rm gas}$ with redshift:

When measuring $f_{\rm gas}$ we adopt a reference cosmology. Since $f_{\rm gas} \propto D_A^{1.5}$, this introduces apparent, systematic redshift variations, depending on differences between adopted and underlying cosmology.

If clusters provide a fair sample of matter content of the Universe then we expect $f_{\rm gas}(z)$ - measured within r_{2500} - to be constant.

When adopted cosmology='true' cosmology, expect $f_{\rm gas}(z) = \rm const.$



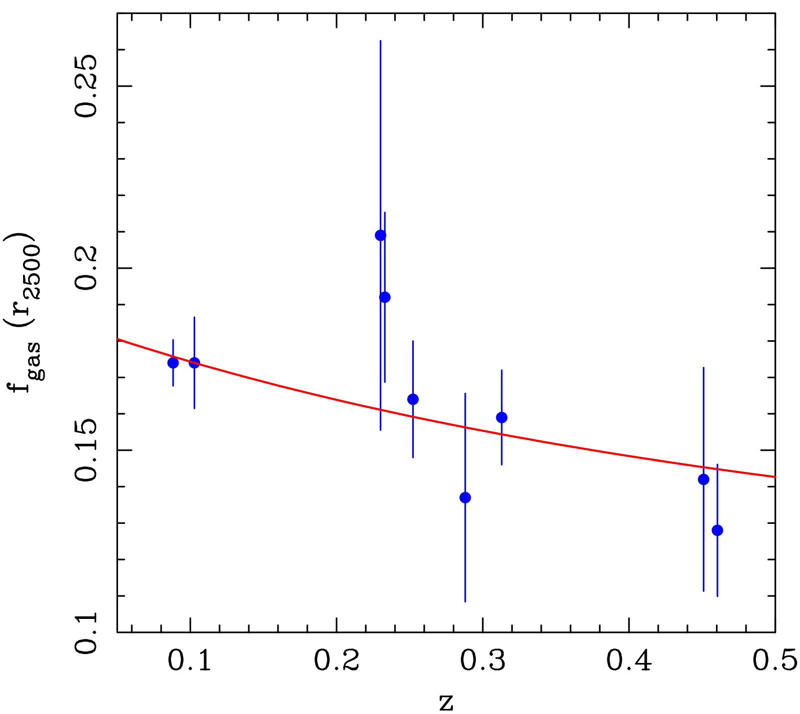
Can easily see $f_{\rm gas}(z)$ data favour ΛCDM over SCDM and that standard ΛCDM ($\Omega_{\rm m} = 0.3, \Omega_\Lambda = 0.7$) close to 'true' cosmology.

Above figures are for older data of Allen *et al.* 2003. Left SCDM. Right ΛCDM (0.3,0.7). Current data used in analysis reported here contains 10 clusters with $z < 0.6$. (Allen *et al.* , in preparation.)

To quantify: fit SCDM data with model which accounts for expected apparent variation in $f_{\mathrm{gas}}(z)$ data as underlying cosmology is varied $(\Omega_{\mathrm{m}}, \Omega_\Lambda) \longrightarrow$ find cosmology giving best-fit to data.

$$f_{\mathrm{gas}}^{\mathrm{mod}}(z) = \frac{b\,\Omega_{\mathrm{b}}}{\left(1+0.19\sqrt{h}\right)\Omega_{\mathrm{m}}} \left[\frac{h}{0.5}\,\frac{D_{\mathrm{A}}^{\Omega_{\mathrm{m}}=1,\Omega_\Lambda=0}(z)}{D_{\mathrm{A}}^{\Omega_{\mathrm{m}},\,\Omega_\Lambda}(z)}\right]^{1.5}$$

$$(\Omega_{\mathrm{b}}\,\mathrm{h}^2 = 0.0214 \pm 0.0020, \quad h = 0.72 \pm 0.08, \quad b = 0.83 \pm 0.04)$$

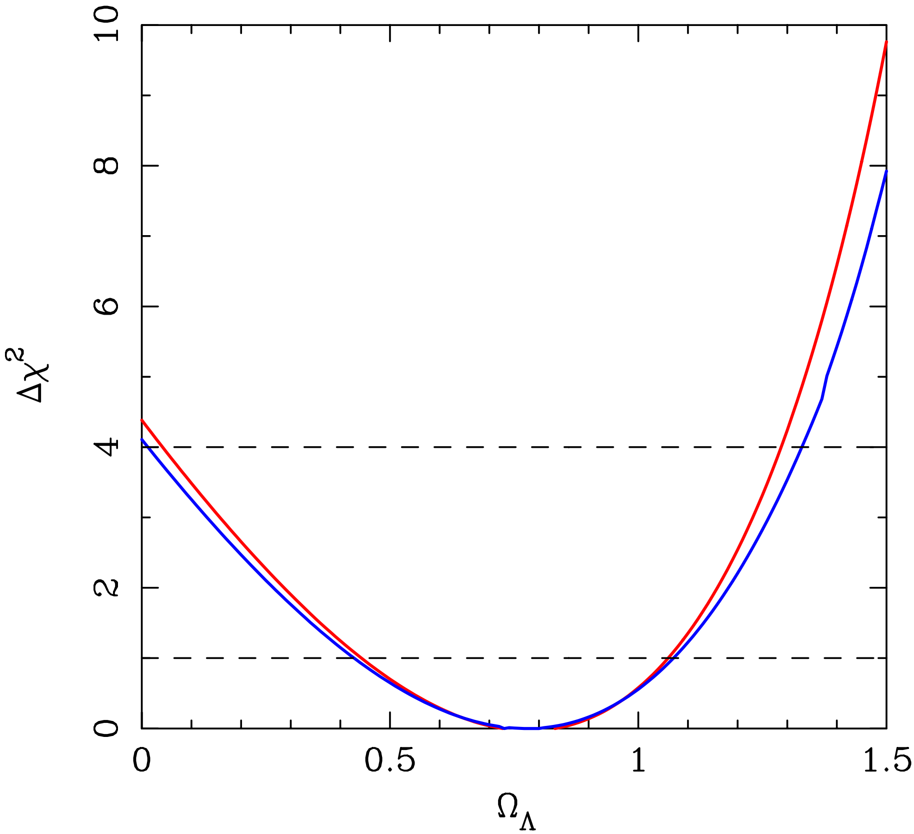


$\Longrightarrow$ Best fit: $\quad \Omega_{\mathrm{m}} = 0.267 \pm 0.034, \quad \Omega_\Lambda = 0.78 \pm 0.33$

Good fit: reduced $\chi^2 \sim 0.6$

(Above figure is for older data. Current data used in analysis here contains 10 clusters. Allen *et al.* , in prep.)

Marginalized results on dark energy (ΛCDM)



Red curve: standard priors

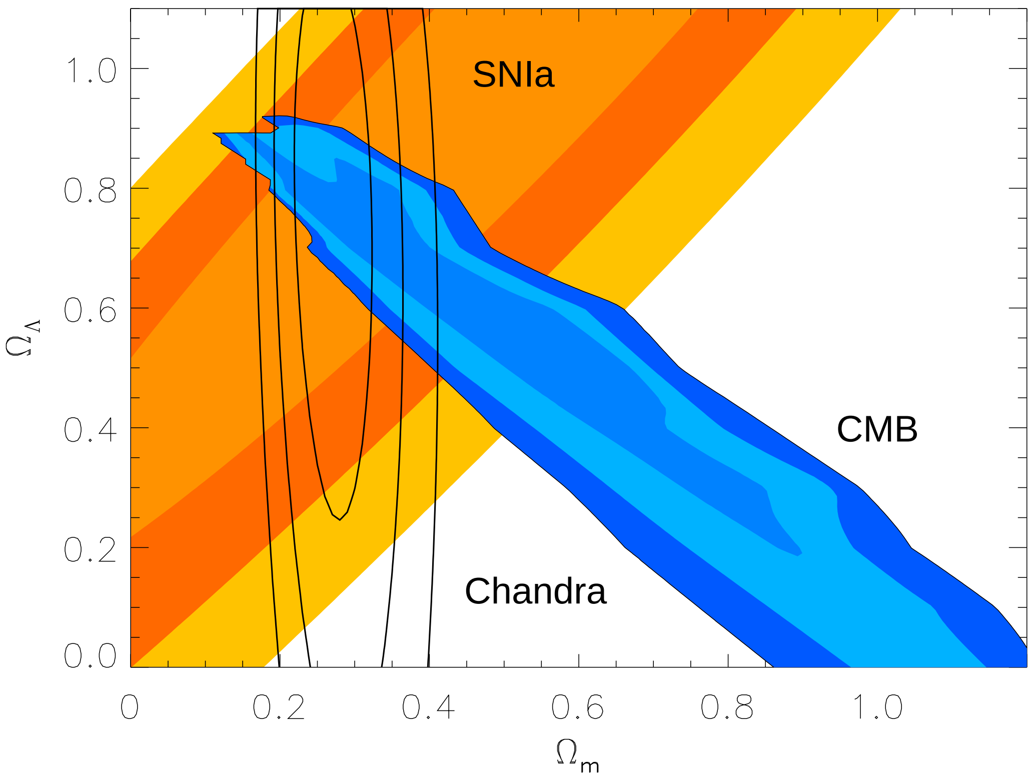
Blue curve: weak priors h=0.72 ± 0.20, $b = 0.83 \pm 0.1$, $\Omega_{\rm b} h^2 = 0.0214 \pm 0.006$

First direct confirmation of SN1a results, revealing effects of dark energy on a single source population as a function of redshift.

Future Chandra/XMM observations could improve significance of detection to $> 4\sigma$ over next few yrs (targets identified) allowing us to probe dw/dz and test nature of dark energy.

(Allen *et al.* , in prep.)

Comparison with independent constraints $\Omega_{\rm m}, \Omega_\Lambda$



Chandra $f_{\rm gas}(z)$ data. $1, 2$ and 3σ contours.
CMB (COBE + Boomerang'98 + MAXIMA-1; Jaffe *et al.* 2001).
Supernovae (Riess *et al.* 1998; Perlmutter *et al.* 1999).

+ also consistent with 2dF + CMB (*e.g.* Efstathiou *et al.* 2002, Lahav *et al.* 2002; Percival *et al.* 2002, Lewis & Bridle 2002).

Agreement between independent analyses/methods.
All results consistent within 1σ statistical uncertainties

$$\Omega_{\rm m} \sim 0.3, \quad \Omega_\Lambda \sim 0.7$$

Constraints on Ω_m and σ_8 from the local X-ray luminosity function of the most X-ray luminous galaxy clusters.

References: *e.g.* Evrard 1989, Henry & Arnuad 1991, Henry *et al.* 1992, Oukbir & Blanchard 1992, White *et al.* 1993, Eke *et al.* 1996, Viana & Liddle 1996, Kitayama & Suto 1997, Borgani *et al.* 1997, Markevitch 1998

THIS ANALYSIS (Allen, Schmidt, Fabian, Ebeling 2003):

1) Local ($z < 0.3$) X-ray luminosity function (XLF) of clusters from ROSAT All-Sky Survey (RASS): eBCS (north) and REFLEX (south) studies (Ebeling *et al.* 2000; Böhringer *et al.* 2002).

2) Mass-luminosity relation from Chandra and ROSAT X-ray observations + weak lensing measurements

→ Precise (M_{200}) mass, luminosity measurements for 17 clusters (including both relaxed and dynamically active systems).

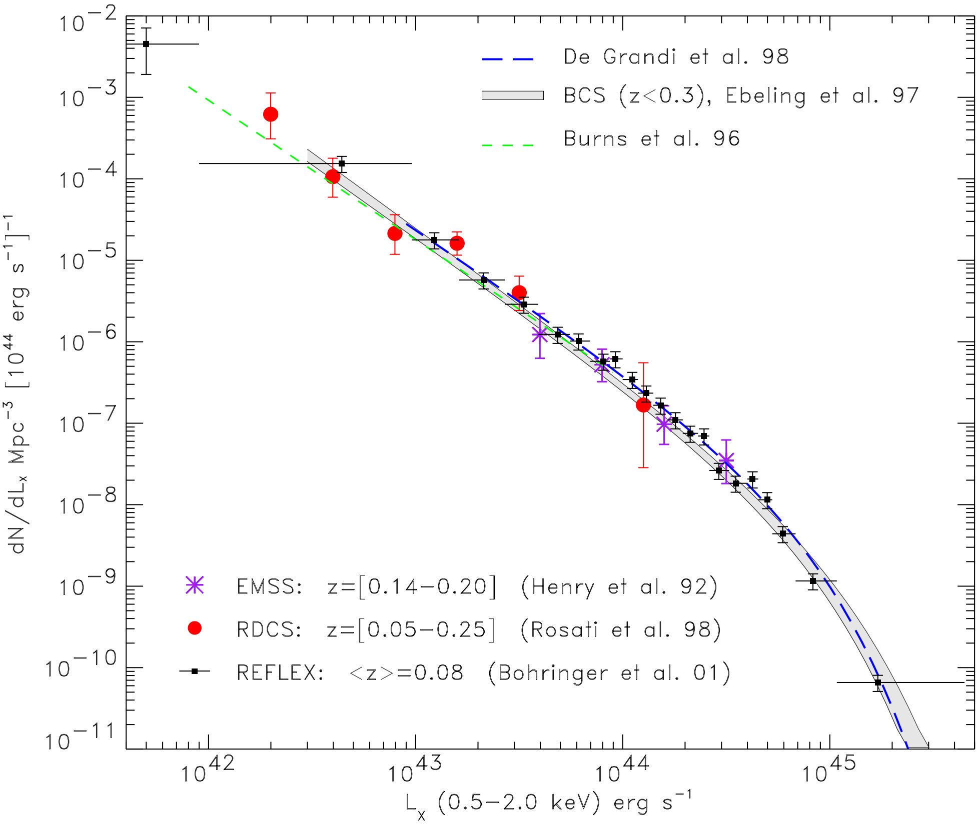
3) Predicted mass function of clusters from Hubble Volume simulations for ΛCDM (Jenkins *et al.* 2001; Evrard *et al.* 2002).

4) Chandra $f_{\rm gas}(z)$ data for dynamically relaxed clusters.

combine → constraints on σ_8 and Ω_m.

The observed local XLF of galaxy clusters

Compilation of recently published samples (Rosati *et al.* 2002):



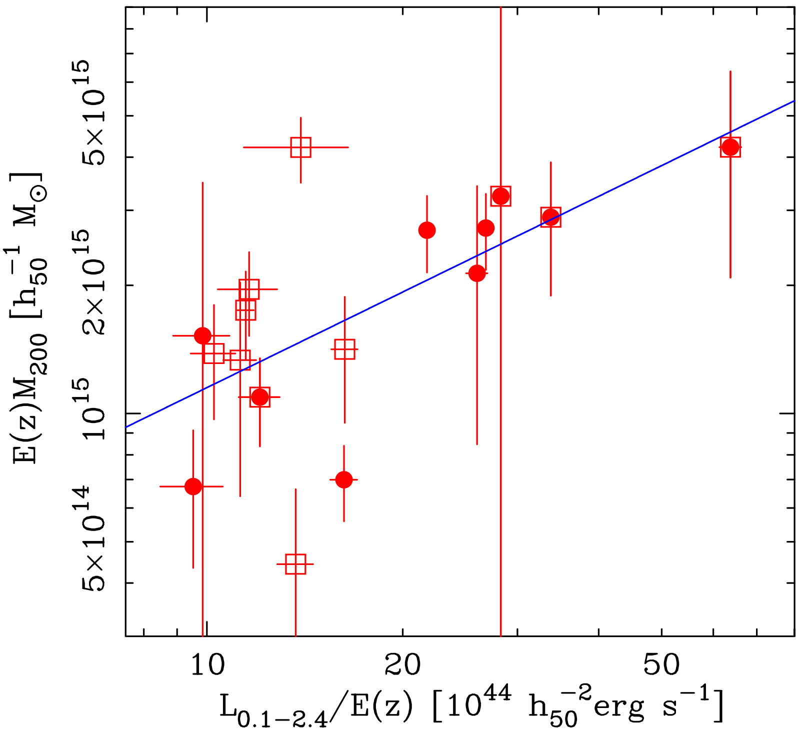
Excellent agreement between independent studies based on ROSAT All-Sky Survey and pointed ROSAT/Einstein observations.

Here, work with XLF from RASS: eBCS (north) and REFLEX (south) studies (Ebeling *et al.* 2000; Böhringer *et al.* 2002).

$\rightarrow$ 111 clusters with $L_{X,0.1-2.4} > 10^{45}\,\mathrm{erg\,s^{-1}}$ $\quad (h = 0.5\ \Lambda\mathrm{CDM})$

Luminosity cut keeps systematic uncertainties to a minimum. These are clusters for which virial relations are calibrated most precisely.

The observed mass-luminosity relation ($\Delta = 200$)



Masses, M_{200}, measured from Chandra and weak lensing data.

$0.1 - 2.4$ keV luminosities from pointed ROSAT observations.

Evolution parameter $E(z) = (1+z)\sqrt{(1 + z\Omega_{\rm m} + \Omega_\Lambda/(1+z)^2 - \Omega_\Lambda)}$ (assume ΛCDM, $h = 0.5$ cosmology to match BCS/REFLEX).

Characterize data using simple power-law model

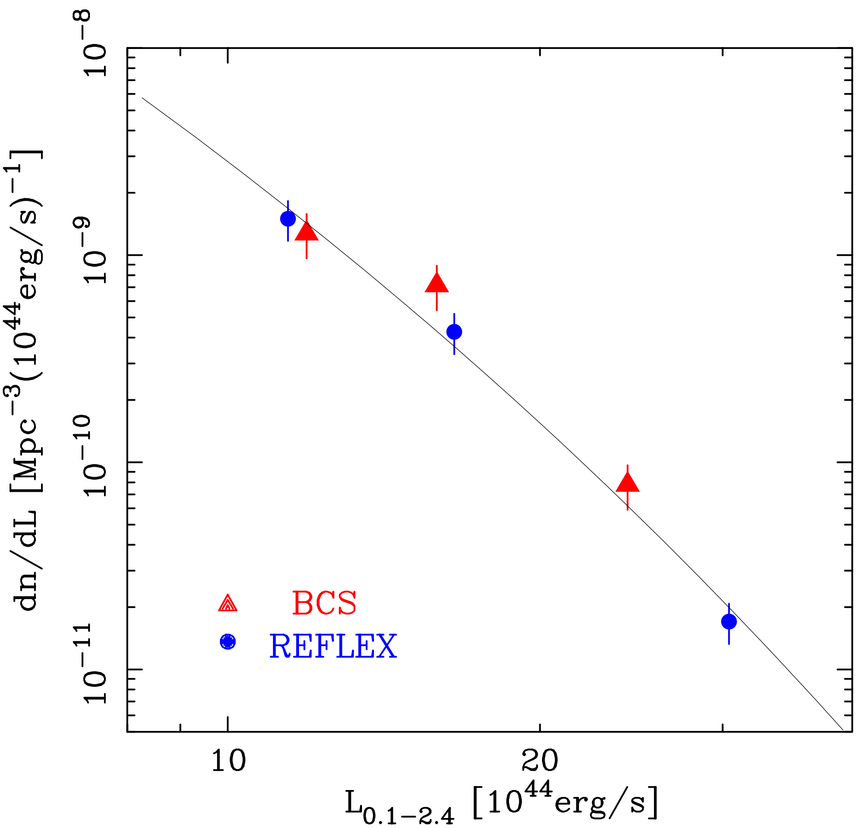
$$E(z)\left[\frac{M_{200}}{1\ \mathrm{M}_\odot}\right] = M_0\left[\frac{L}{E(z)\,10^{44}\,\mathrm{erg\,s^{-1}}}\right]^\alpha.$$

($M_0 = 2.0 \pm 1.0 \times 10^{14}\,\mathrm{M}_\odot$, $\alpha = 0.76 \pm 0.15$)

Construct model XLF

Combine observed mass-luminosity relation + predicted mass function (Evrard *et al.* 2002) $\rightarrow$ predicted model XLF (σ_8, Ω_m).

Fit model XLF to observed XLF $\rightarrow$ constraints on σ_8, Ω_m.



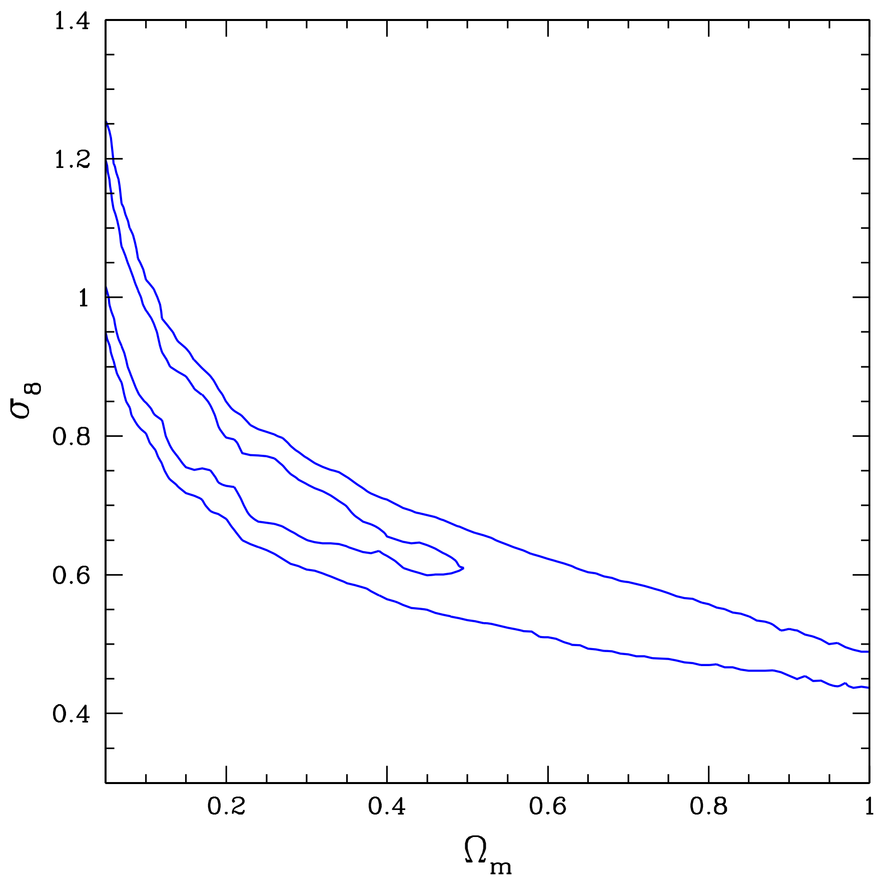
Simple χ^2 approach:

Using best-fit M-L relation, we find that model with $\sigma_8 = 0.73$, $\Omega_\mathrm{m} = 0.25$ provides best fit to the observed XLF ($\chi^2_\mathrm{min} = 5.1/4$).

Results on σ_8 as a function of Ω_m

Use Monte Carlo analysis which accounts for effects of scatter as well as uncertainties in norm and slope of M-L relation.

Flat ΛCDM cosmology:

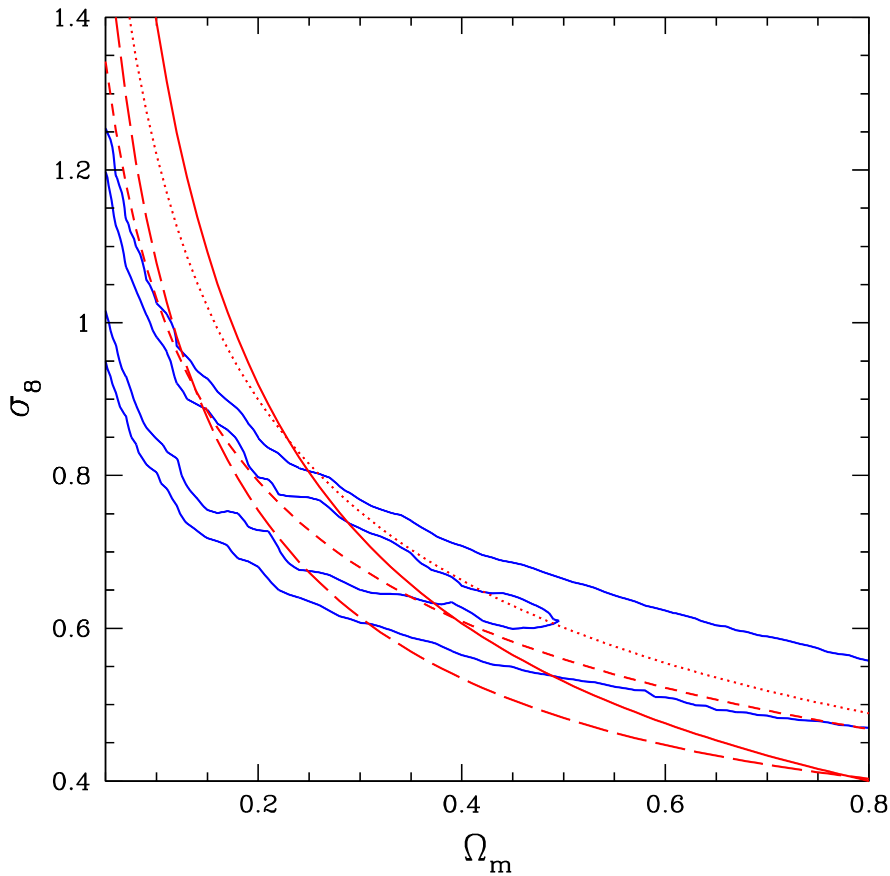


$$\sigma_8 = (0.508 \pm 0.019)\,\Omega_m^{-(0.253\pm0.024)}$$

$$\Omega_m < 0.34$$

Comparison with independent results (flat ΛCDM)

Other studies based on local cluster abundance



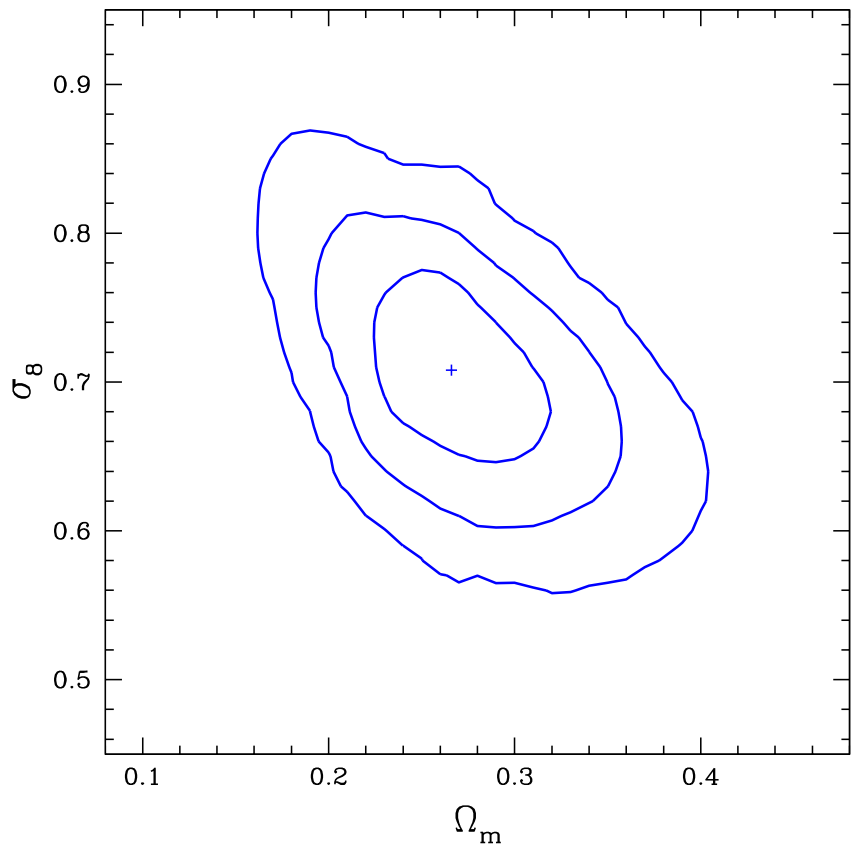
Seljak (2002). Local XTF, observed M-T
Reiprich & Böhringer (2001). Local XTF, observed M-T
Viana *et al.* (2002). Local XLF . Stacked lensing M-L
Bahcall *et al.* (2002). Optical (SDSS) clusters, mass-richness

Consistent with local XLF, XTF analyses of Schuecker *et al.* (2003), Pierpaoli *et al.* (2003) + study of local baryonic mass function by Voevodkin & Vikhlinin (2003).

Breaking the $\sigma_8 - \Omega_\mathrm{m}$ degeneracy

The degeneracy between σ_8 and Ω_m from local XLF/XTF studies can be broken by combining with Chandra $f_\mathrm{gas}(z)$ data.

Include Gaussian priors: $\Omega_\mathrm{b}\,\mathrm{h}^2 = 0.0205 \pm 0.0018$, $h = 0.72 \pm 0.08$
$b = 0.83 \pm 0.04$, $\quad \Omega_\mathrm{k} = 0.0$.

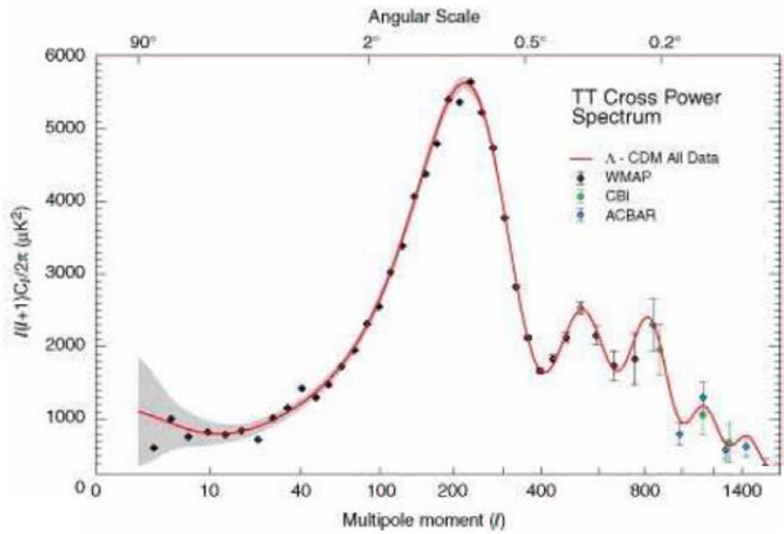


$\longrightarrow$ Best-fit and marginalized 68 per cent confidence limits:

$$\sigma_8 = 0.71 \pm 0.04$$

$$\Omega_\mathrm{m} = 0.27 \pm 0.03$$

Cosmological constraints from CMB+$f_{\rm gas}(z)$ data.



Extended WMAP data set

WMAP (TT/TE) +CBI+ACBAR

Analyse CMB (WMAP+CBI+ACBAR) data using MCMC method. Importance sample the results folding in $f_{\rm gas}(z)$ constraints.

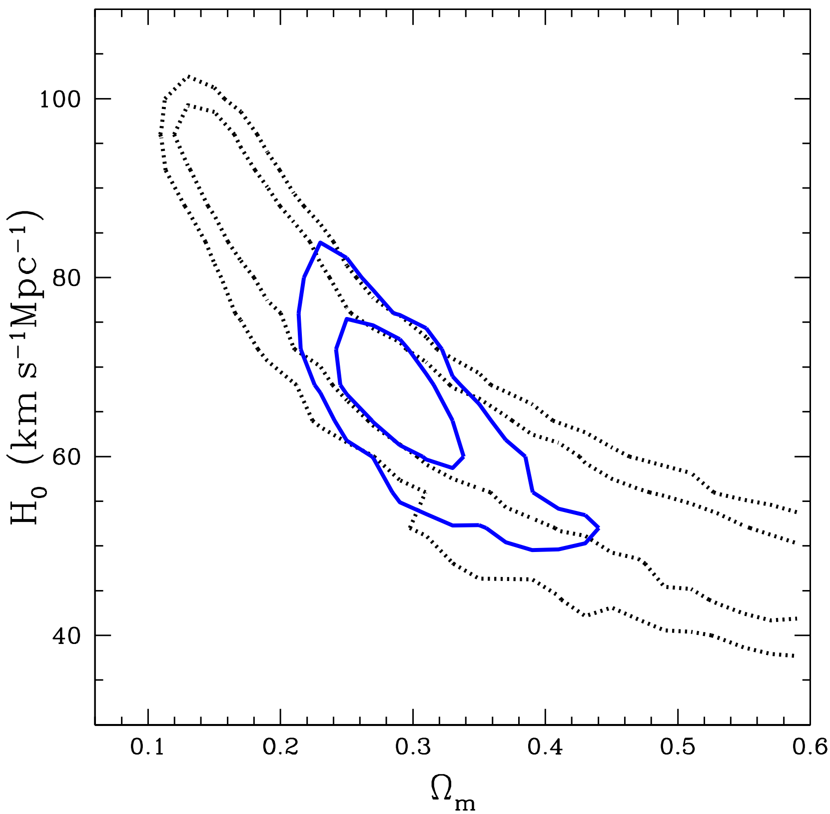
Use 8 parameter model with free parameters

$\Omega_{\rm dm}h^2$	physical dark matter density
$\Omega_{\rm b}h^2$	physical baryonic matter density
H_0	Hubble constant
$A_{\rm S}$	scalar amplitude
$n_{\rm S}$	scalar spectral index
$z_{\rm rec}$	redshift of recombination
$\Omega_{\rm k}$	spatial curvature
w	quintessence parameter $= p/\rho$
R	tensor/scalar amplitude ratio
$n_{\rm T}$	tensor spectral index
f_ν	neutrino mass fraction

Combination of CMB+$f_{\rm gas}(z)$ data breaks degeneracies present in both data sets

$$f_{\rm gas}^{\rm mod}(z) \propto \frac{\Omega_{\rm b}}{\Omega_{\rm m}} \left[\frac{h}{0.5} \, \frac{D_{\rm A}^{\Omega_{\rm m}=1, \Omega_{\rm q}=0}(z)}{D_{\rm A}^{\Omega_{\rm m}, \Omega_q}(z)} \right]^{1.5}$$

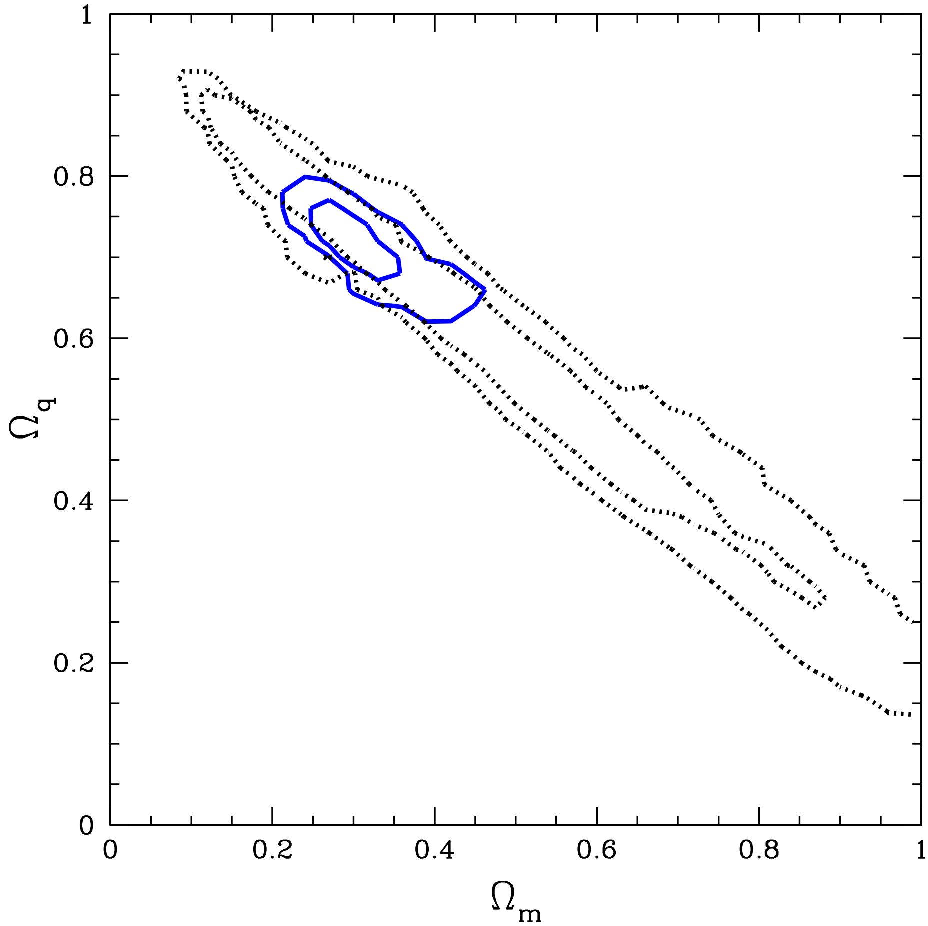
e.g. constraints on $\Omega_{\rm m}$, H_0 ($\Omega_{\rm k}$ free, w free)



Black: CMB only Blue: CMB+$f_{\rm gas}(z)$

$$\Omega_{\rm m} = 0.29^{+0.04}_{-0.03}, \quad H_0 = 68 \pm 6 \ \ {\rm km\,s^{-1}\ Mpc^{-1}}$$

Dark energy density: quintessence models ($\Omega_{\rm k}$, w free)



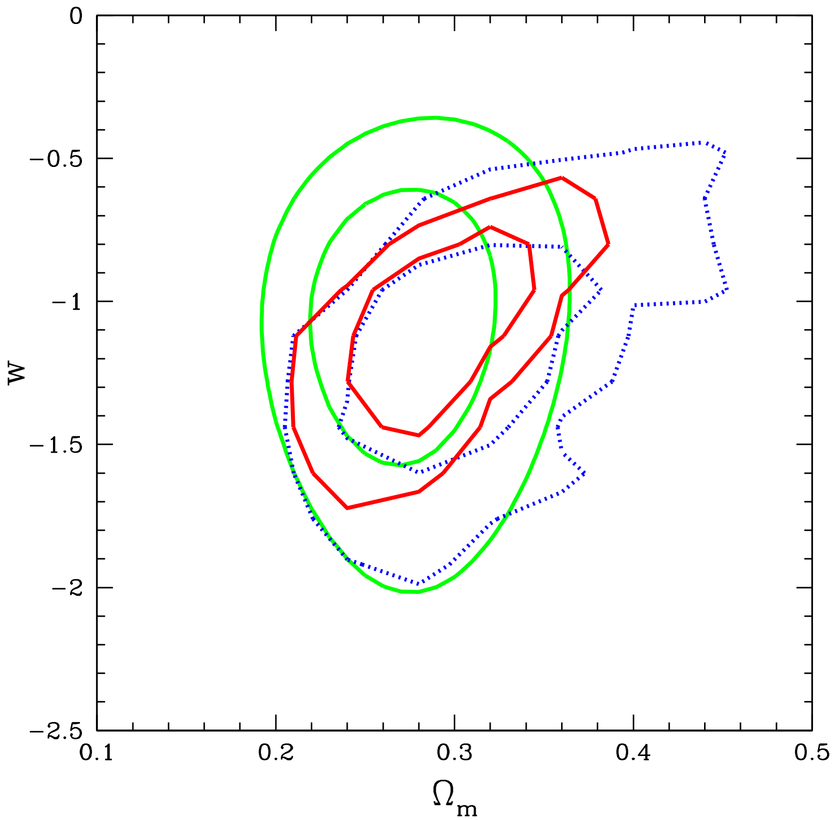
Black: CMB only   Blue: CMB+$f_{\rm gas}(z)$

Marginalized results:

$$\Omega_{\rm m} = 0.29^{+0.04}_{-0.03},\ \ \Omega_{\rm q} = 0.73^{+0.03}_{-0.04}$$

(Allen *et al.* , in prep.)

Quintessence parameter ($w \equiv p/\rho$)



Marginalized results:

$$f_{\rm gas}(z)\text{+CMB } (\Omega_{\rm k} \text{ free}) : w = -1.17 \pm 0.26$$

$$f_{\rm gas}(z)\text{+CMB } \quad (\text{flat}) \quad : w = -1.02^{+0.17}_{-0.31}$$

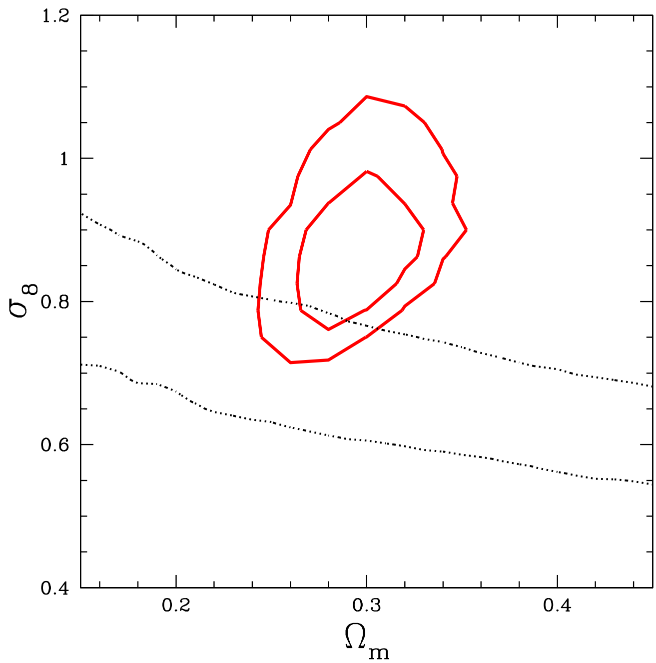
$$f_{\rm gas}(z)\text{+BBNS+HST (flat)} : w = -1.04^{+0.31}_{-0.36}$$

$\longrightarrow$ results consistent with $w = -1$ (ΛCDM)

(Allen *et al.* , in prep.)

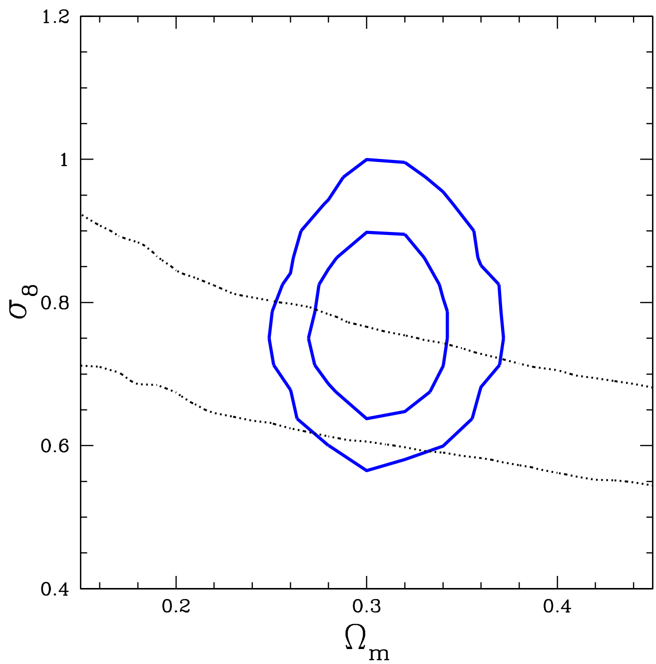
Preference for a non-zero neutrino mass

CMB+2dF+$f_{\rm gas}(z)$ data: Flat geometry, w=-1, allow tensors.



Assuming negligible neutrino mass

$f_\nu = \Omega_\nu/\Omega_{\rm m} = 0$

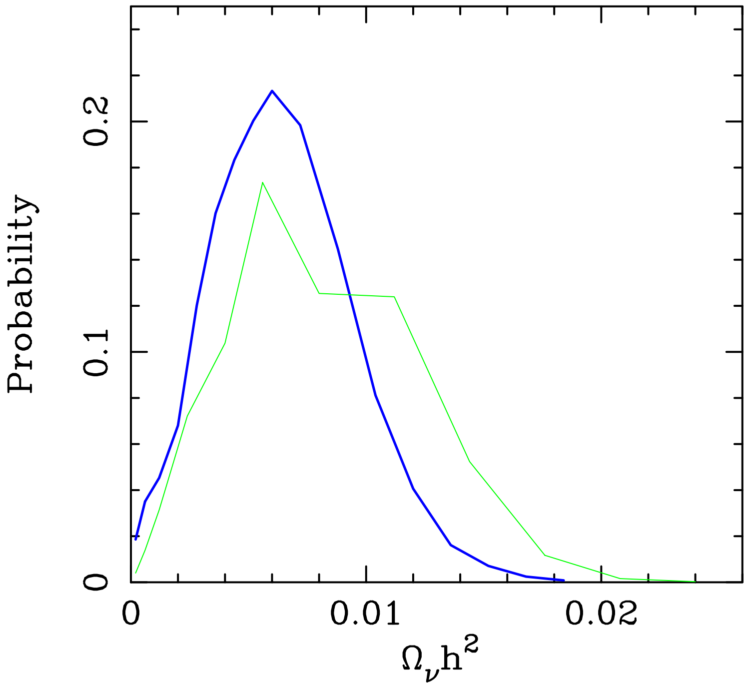


With neutrino mass as free parameter

$\rightarrow\ \Omega_\nu/\Omega_{\rm m} = 0.05$

(Allen, Schmidt & Bridle 2003)

Marginalized constraints on neutrino density



Blue: CMB+2dF+$f_{\rm gas}$+XLF

Green: CMB+$f_{\rm gas}$+XLF

Tentative detection of non-zero species-summed neutrino mass

$$\sum_i m_i \sim 94\,\mathrm{eV}\,\Omega_\nu h^2 = 0.56^{+0.30}_{-0.26}\,\mathrm{eV}$$

Given small mass-squared differences from solar and atmospheric neutrino experiments, and assuming 3 active neutrino species (SLAC, LEP) and an absence of massive, sterile neutrinos

→ Approximately degenerate neutrino mass.

$$m_\nu = 0.19^{+0.10}_{-0.09}\,\mathrm{eV} \qquad (\mathrm{CMB{+}2dF{+}}f_{\rm gas}\mathrm{{+}XLF})$$
$$m_\nu = 0.17^{+0.22}_{-0.05}\,\mathrm{eV} \qquad (\mathrm{CMB{+}}f_{\rm gas}\mathrm{{+}XLF})$$

Consistent with 2dF team ($\sum_i m_i < 2.2\,\mathrm{eV}$) and marginally with WMAP-team, including Ly-α forest data ($\sum_i m_i < 0.71\,\mathrm{eV}$)

CONCLUSIONS

Chandra + grav. lensing data $\longrightarrow$ precise mass measurements for dynamically relaxed clusters. Mass profiles well described by NFW models with parameters $(r_{\rm s}, c)$ consistent with simulations.

Chandra $f_{\rm gas}(z)$ data for relaxed clusters in combination with other data $\longrightarrow$ tight constraint on mean matter density of Universe, $\Omega_{\rm m}$.

$$f_{\rm gas}(z) + \mathrm{BBN} + \mathrm{HST} \longrightarrow \Omega_{\rm m} = 0.27 \pm 0.03$$
$$f_{\rm gas}(z) + \mathrm{CMB} \longrightarrow \Omega_{\rm m} = 0.29^{+0.04}_{-0.03}$$

Chandra $f_{\rm gas}(z)$ data $\longrightarrow$ direct confirmation of SN1a results on DE and interesting constraints on quintessence.

$$f_{\rm gas}(z) + \text{weak priors} \longrightarrow \Omega_{\Lambda} = 0.78 \pm 0.33$$
$$f_{\rm gas}(z) + \mathrm{CMB} \longrightarrow \Omega_{q} = 0.73^{+0.03}_{-0.04}$$
$$\longrightarrow w = -1.17 \pm 0.26$$

Local XLF + observed M/L $\longrightarrow$ tight constraint on amplitude of mass fluctuations on $8\,h^{-1}$Mpc scales, $\sigma_8 \sim 0.7$ for $\Omega_{\rm m} \sim 0.3$.

Combination of CMB + 2dF + $f_{\rm gas}(z)$ + XLF data $\longrightarrow$ preference for a non-zero neutrino mass $\longrightarrow m_\nu = 0.19^{+0.10}_{-0.09}$ eV.